Chapter 5
Design Analysis of Tidal Inlets

5-1. Introduction

a. Design considerations.

(1) Engineering design of coastal inlets typically involves either improving an existing inlet or developing a new inlet. In either case, engineers must realize that the design project is in a dynamic environment where natural processes are not completely understood. Extreme care should be exercised with any alteration to existing shoreline and bathymetric configurations. Not necessarily all physical changes will upset the natural environment; the ability to anticipate project impacts and implement appropriate measures to alleviate adverse effects is the key to successful design practice. Mathematical and physical models are important tools to be applied in inlet design analysis.

(2) It is equally important that the designed features perform their intended functions with minimum maintenance requirements. Design criteria should be established to guide the design of each feature for both functional performance and structural integrity under adverse environmental conditions such that project benefits will be maximized. A net-benefit optimization analysis is required to determine the economic optimum design.

b. Design features. Most designs for tidal inlets are navigation or navigation-related projects but consideration is also given to water quality improvement, sediment control, and recreation. Structural improvements for navigation projects may include the construction of jetties, breakwaters, or bulkheads and revetments. Jetties and breakwaters have similar structural configurations but differ in performance functions. Jetties are designed mainly to prevent navigation channels from shifting and shoaling while breakwaters are built to reduce wave energy in sheltered areas. With these objectives in mind, the alignment, layout, and length of the structure elements must be analyzed for optimum performance. Bulkheads and revetments are shoreline erosion protection structures. Nonstructural navigation improvements include channel dredging and sand bypassing.

c. Physical environmental data. Physical environmental data are required for better understanding of natural transport processes at inlet systems, development of design criteria, assessment of functional performance of designed structures, and determination of impacts on natural littoral processes within the tidal inlet system. These data include: tidal elevations and currents, freshwater inflows, winds and waves, water quality parameters, bathymetry, and geological information. In addition, weather data related to visibility and ice information may also be needed for the design analysis.

d. Sources of information. A substantial quantity of environmental data is available in the public domain and can be obtained from public or university libraries, Government agencies, and data retrieval and referral centers. Tidal data are readily available from the publications of Tide Tables, Tidal Current Tables, and Tidal Bench Marks by the NOS. Field measurements of tidal currents should be planned for engineering analysis. River flows into the tidal basin, sediment loads, and other water quality parameters are provided in the *Water Resources Data* published annually by the U.S. Geological Survey. Nautical charts and bathymetric maps published by NOS are usually adequate for preliminary engineering design and analysis. Baseline bathymetric surveys should be scheduled for planning and design purposes. Coastal geologic data, and wind and wave data generally are scarce, but Chu, Lund, and Camfield (1987) provide a listing of useful data sources for design analysis.

5-2. Navigation Channel Design

a. General. Engineering analysis of navigation channels involves identifying appropriate design criteria, determining the most economical channel dimensions, analyzing of dredging requirements, and determining dredging effects on overall inlet stability. Only entrance channel design analysis is discussed in this manual. EM 1110- 2-1613 and EM 1110-2-1615 should be consulted in the formulation of channel features. The following factors influencing channel design need careful evaluation: design vessel; tides and design water levels; winds, waves, currents, and sedimentation.

b. Design vessel. The design vessel or vessels are selected from comprehensive studies of the various types and sizes of vessels expected to use the project during its design life. Channel dimensions should be selected to safely and efficiently accommodate the amount and type of traffic anticipated. The design vessel is selected by evaluating trade-offs of the delay cost incurred by larger vessels and cost of increased channel dimensions. The maximum size vessel and least maneuverable vessel in the fleet must be able to make a safe transit; however, the following special conditions may be important considerations:

(1) Suitable wind, wave, and current conditions and visibility.

(2) Use of high tide for additional water depth.

(3) Speed restrictions to reduce squat, ship-generated wave heights, and shore damage.

(4) One-way traffic.

(5) Tugboat assistance.

(6) Provision of anchorage area.

c. Tides and design water levels. The NOS publishes tide height predictions and ranges. Figure 5-1 shows spring tide ranges for the continental United States. Historical records on tidal elevations, including extreme high water, mean higher high water, mean high water, mean tide level, mean low water, mean lower low water, and extreme low water, may be found from Tidal Bench Marks published for each NOS tide station. Cumulative probability of tidal elevations prepared by Harris (1981) can be useful in the analysis of frequency and duration of ship delays. In addition to ocean tides, water level is also affected by storm surges, seiches, and river discharges. Design water level may vary with design functions of specific project features. Lower low water levels are normally used to determine available and needed depths for various size vessels and designs for structure toes. High-water levels are used to determine wave penetration, structure height, and armor layer design.

d. Winds, waves, and currents.

(1) Estimates of winds, waves, and currents are needed to determine their effects on vessel motions and controllability, and to estimate sediment movement in the project area. Wind data are available from the National Climatic Data Center (Federal Building, Asheville, NC 28801). Estimates of wind waves and vessel-generated waves are needed for various elements of project design. Predictions of wind-generated waves can be made by using the techniques presented in EM 1110-2-1414. Vessel-generated waves can be estimated with methods presented in EM 1110-2-1615. Coastal currents are affected by tides, river discharges, seiche motions, wind waves, and coastal structures. Tidal currents published by NOS may be adequate for preliminary project analysis. Improvements such as dredging and jetty or breakwater construction will affect current conditions in the project area. Mathematical or physical model simulations of current as well as wave distributions may be necessary for detailed design analysis. Simulations of ship transits may be required to ensure that the channel design is in compliance with functional design criteria.

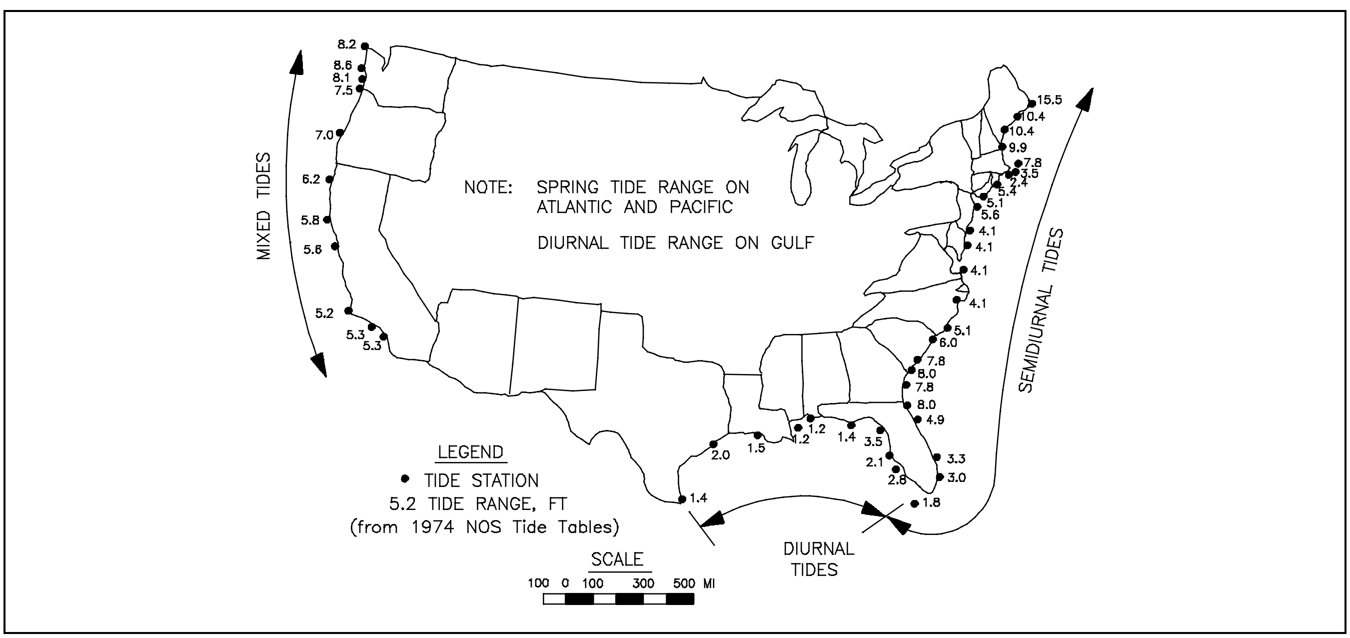

Figure 5-1. Ocean spring tide ranges

(2) One design problem of note, particularly of concern to small boat harbors, is the breaking of waves in the entrance channel during higher wave energy and/or higher flow discharge events. The following guidance is summarized by the Members of the Task Committee on Marinas 2000 (American Society of Civil Engineers (ASCE) 1992). Linear wave theory can be used to calculate a minimum breaking wave depth (SPM 1984) based on the design wave (or waves) to establish a minimum safe channel depth. Analytical methods are available to calculate the effects of ebb tidal flow and/or river flow given incident wave conditions (SPM 1984). By then adding allowances for design vessel motions such as roll, pitch, and heave (EM-1110-2-1615) a minimum depth for safe navigation can be specified. Adverse entrance conditions, caused by waves, can be minimized through the following: greater entrance depths, which will allow higher storm waves before breaking; channel widths widened to allow more maneuvering room during higher sea conditions (EM 1110-2-1615); structures such as jetties can be extended offshore to reach deeper depths thus allowing higher unbroken waves across the ebb bar; and offshore structures such as breakwaters can be constructed to provide shelter to the entrance (EM 1110-2-2904). Many small boat harbor designs have been evaluated and improved based on physical model tests (Bottin 1992).

e. Sedimentation. Aspects of sedimentation that must be considered include the characteristics and transport of native sediment as well as that of sediment introduced into the project area by littoral drift and river flow. Sediment budget and shoaling analyses should be performed before and after construction. These studies provide the basis for maintenance dredging requirements, and shoreline erosion and inlet stability control measures. Detailed discussions of sediment budget methodology are presented in Chapter 4, EM 1110-2-1502, and the SPM (1984).

f. Channel depth.

(1) Wave conditions. Allowance for wave action is required for design depth determination. For small craft, one half of the design wave height is generally adequate. Pitch, roll, and heave should be evaluated for larger vessels that use the channel. Large vessel motions can be determined by physical or mathematical model simulations or data from prototype observations. The effect on wave heights and directions in the channel due to depth change (shoaling and refraction over the ebb tidal delta) and the effect on wave period due to currents should be analyzed in the study of vessel motions and determining a safe entrance channel depth.

(2) Dredging tolerance. Dredging tolerance is taking into account the inaccuracies of dredging operations in marine environments in relation to the theoretical design channel cross section. Usually a value ranging from 0.3 to 0.9 m (1 to 3 ft) is used in contract specification.

(3) Advanced maintenance. Channel maintenance usually consists of removing sediment deposits from the channel bed. In channels where shoaling is continuous, overdredging is a means of reducing the frequency of dredging while providing reliable channel depth over longer periods of time. Advance maintenance consists of dredging deeper than the safe channel design depth to provide for accumulation and storage of sediment. Justification for advance maintenance is based on channel depth reliability and economy of less frequent dredging. Estimates of channel shoaling rates are used in the justification for advance maintenance dredging. Several depths should be considered to optimize the advanced maintenance allowance; however, deeper channels will tend to be more efficient sediment traps and could shoal more rapidly. Overdepth advanced maintenance eliminates the need for a dredging tolerance allowance.

g. Channel width. Factors to be considered in channel width design are discussed in EM 1110-2-1613. Certain shoaling patterns may warrant the consideration of advanced maintenance in the form of a channel widener. Such sediment traps are also justified based on the reduction of dredging frequency and increase in channel reliability. Navigation in the entrance channel is often affected by strong and variable tidal currents, rough seas, breaking waves, wind, fog, and other difficulties. Channel width, including advanced maintenance channel wideners in the entrance, should be judiciously selected based on an analysis and evaluation of conditions at each project. A review of methods for determining channel widths as presented in Corps of Engineers reports is included as Appendix B of EM 1110-2-1613.

h. Channel side slope.

(1) Significant factors in the design of side slopes for navigation channels include bottom soil type, slope location, seismic activity, and ease of construction. Most noncohesive soils will not stand at a slope angle greater than 45 deg. Cohesive soils will stand initially at much higher angles, but over a period of time, they tend to degrade. Table 5-1 shows various side slopes for underwater channels.

Table 5-1
Typical Side Slopes for Various Soil Types (Bray 1979)

Soil Type	Side Slope (V:H)
Rock	Nearly vertical
Stiff clay	1:1
Firm clay	1:1.5
Sandy clay	1:2
Coarse sand	1:3
Fine sand	1:5
Mud and silt	1:8 to 1:60

(2) In practice, it usually is found that characteristics other than inherent slope stability are the controlling factors. Consideration should be given to the slope location and whether the slope is totally or partially submerged. A partially submerged slope acts as a beach and therefore, is liable to assume a beach slope. Side slopes must be constructed by dredges in a manner which suits the dredging operation. In certain cases, very steep slopes are difficult and expensive to construct. In these circumstances, savings in dredging quantities may be completely offset by increase in unit cost of dredging. Generally slopes of 1:3 or less do not cause major dredging problems.

i. Channel dredging. Channel dredging involves initial construction to provide the design depth, with provisions for advance maintenance dredging, dredging tolerance, and periodic maintenance. Cost estimation for both construction and maintenance dredging should be made for various channel alignments and dimensions. Deep-draft channels usually are dredged by hopper dredges in areas exposed to wave action or where disposal is in exposed offshore or estuarine areas. Pipeline dredges are usually more economical with greater production with soft material but are restricted to protected or semi-protected areas. Dredged material can be disposed of in open water or behind confined dikes. Contaminated material is generally disposed of behind containment dikes with careful monitoring of return water quality. If the dredged material is of reasonably good quality, it should be considered for beach nourishment or landfill purposes. EM 1110-2-5025 provides guidance on dredging, disposal, and beneficial uses of dredged material.

5-3. Jetties

a. Design principles. A jetty system helps to deepen an inlet channel and reduce required dredging by concentrating and directing tidal currents to optimize scouring action. This is accomplished by confining discharge areas and making flow channels more hydraulically efficient, thereby promoting higher channel velocities. Jetties stabilize an inlet entrance by intercepting the littoral drift and preventing or minimizing deposition in the inlet channel. Jetties also minimize the effect of wave action and cross-currents on vessels transiting an inlet. As a permanent coastal structure protruding into the active littoral zone, jetties alter natural sediment transport processes. Construction of a jetty system includes features or provisions to mitigate any significant adverse effects, such as downdrift beach erosion or removal of valuable sand from the littoral system. EM 1110-2-2904 provides the structural design aspects of jetty systems.

b. Design theories.

(1) General. Existing jetty systems can be grouped into two basic designs, single jetties and twin jetties. The following discussion addresses the design theory and functional design criteria of each. (Note: In most cases, two jetties are needed to keep littoral drift from entering the channel. Because single-jetty systems have been found to be unsatisfactory, single-jetty construction is no longer recommended; however, the design theory of such systems will be presented as an aid in evaluating those already in existence.)

(2) Single jetties.

(a) A single straight jetty or curved jetty may be oriented perpendicular to the shoreline or may be placed at an angle with the shoreline depending on predominant wave direction, channel alignment of the natural inlet, and desired alignment of the improved inlet. A single updrift jetty is attached to shore on the updrift side of the channel entrance to act as a barrier to the movement of littoral drift alongshore from the net transport direction, as shown in Figure 5-2.

(b) Two variations to the basic single updrift jetty are the addition of a weir section and the Haupt jetty. A weir section is a low section with a crest elevation near mean sea level at the shore end. Sediment is transported over the weir by waves and currents into a deposition basin that is periodically dredged. With this design, the littoral drift from the updrift direction is trapped and localized in the basin before it reaches the navigation channel. Methods of deposition basin storage analysis, weir section design, and updrift beach profile design are provided by Weggel (1981). Figure 5-3 is a schematic of such a jetty system constructed at Masonboro Inlet, North Carolina. (Note: Due to unsatisfactory performance of the single-jetty system, Masonboro Inlet now has two jetties.)

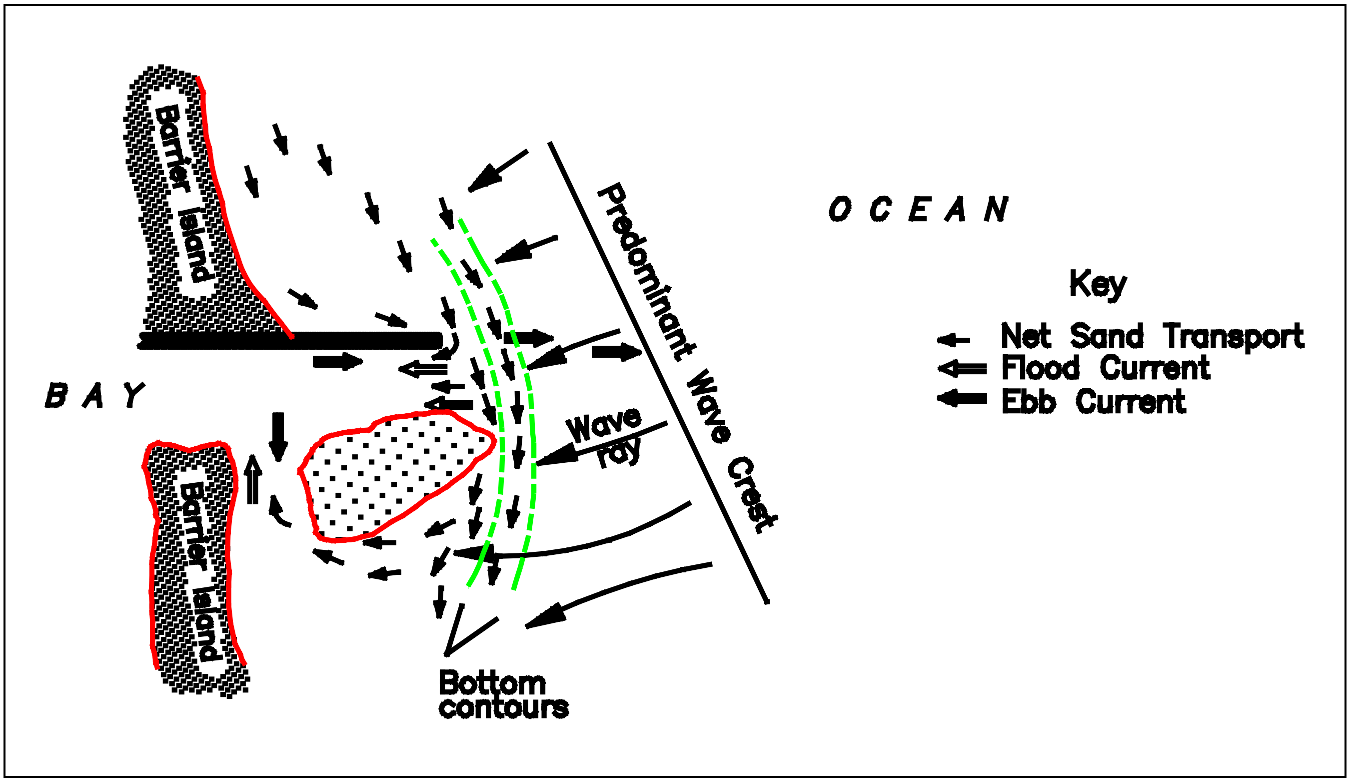

Figure 5-2. Schematic of single updrift jetty

(c) The Haupt jetty is a single curved jetty which is detached from the shoreline and located on the updrift side of an entrance channel. The jetty is concave to the main ebb-tidal currents to force the ebb current against the jetty and scour a well-defined channel. Being detached from shore, the system, as shown in Figure 5-4, readily admits flood currents to increase the tidal prism, thus permitting greater discharge through the channel during ebb tide.

(d) Single jetties located on the downdrift side of an inlet entrance permit the net longshore transport of sand from the updrift direction to force the channel against the jetty as shown by Figure 5-5. In this case, the ebb current controls channel scour activities. Kieslich (1981) discusses the response of entrance channel behavior following the construction of 13 tidal inlets in the United States. The study concluded that the construction of single jetties resulted in migration of the channel thalweg towards the jetty regardless of the inlet-bay orientation, angle of the jetty to the shoreline, position of the jetty relative to the direction of net longshore transport, the ratio of net-to-gross transport, or the gross transport.

(3) Twin jetties.

(a) The two jetties of a double-jetty system may be placed perpendicular to or at an angle with the shoreline; may be curved or straight and converging, diverging, or parallel; and may be equal or unequal in length, depending on the local conditions at the entrance. Figure 5-6 shows a typical twin-jetty system. A double-jetty system may be the original design or the later addition of a second jetty to a single-jettied entrance. Twin jetties are normally aligned parallel with the selected channel alignment; this design most effectively controls channel flow velocities. Converging alignments (arrowhead type) are generally not satisfactory since they are more costly to construct due to greater length, they do not reduce wave action more than parallel jetties, they trap more sediment, and they often allow channel meandering.

(b) The distance between jetties should be designed by considering channel width, maximum current speed within the inlet entrance, and stability of bottom material, as well as overall inlet entrance stability. Jetty lengths are determined by the channel project depth and

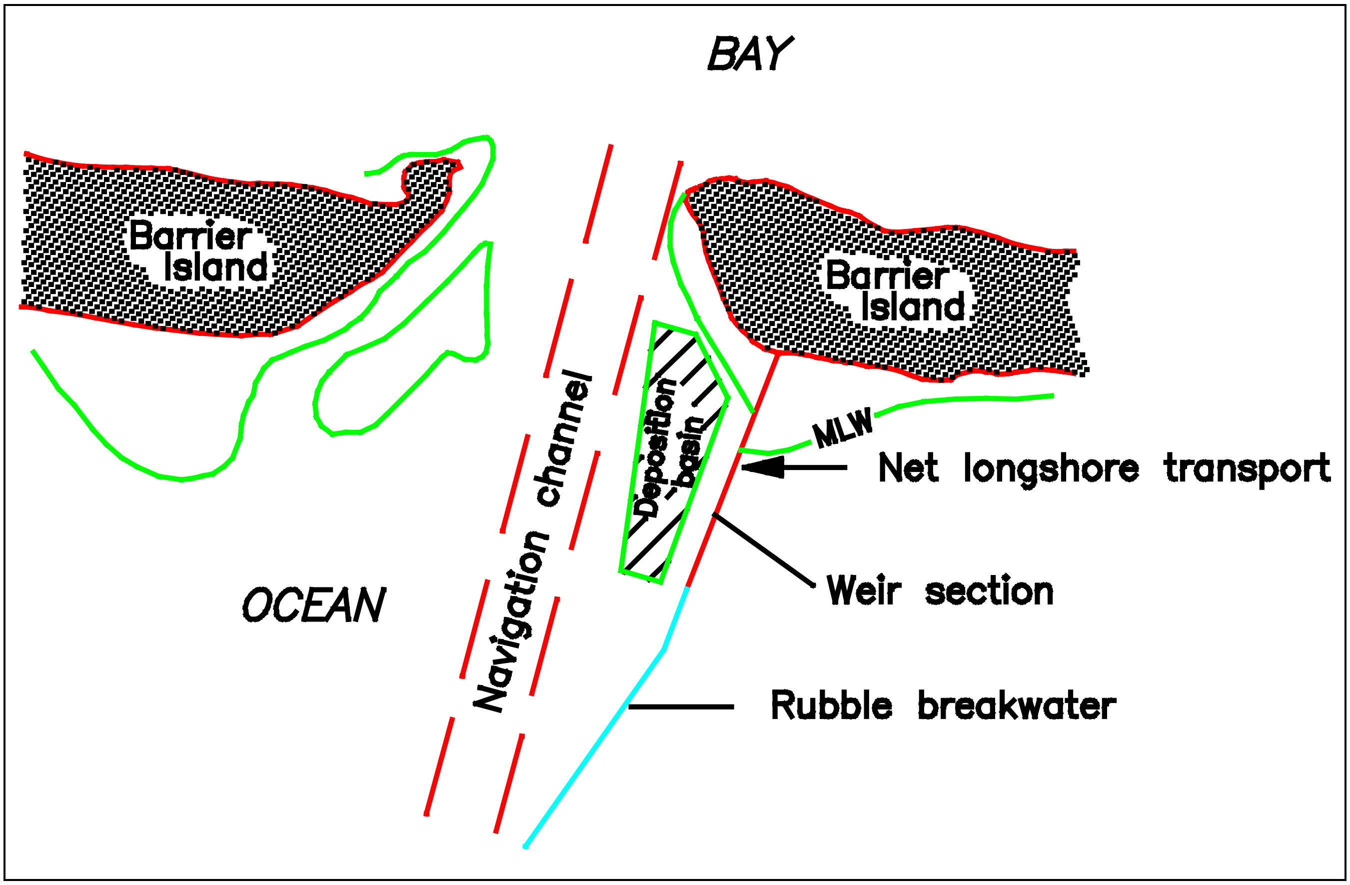

Figure 5-3. Schematic of a weir section in a jetty system

characteristics of the local littoral system. Although each project must be analyzed independently, a general rule suggests that jetties extend to the ocean contour equivalent to the dredged channel depth. Hydraulic model tests are generally advisable for jetty layout to optimize alignment and lengths. Additional information on jetty and channel layout can be obtained from EM 1110-2-2904, EM 1110-2-1613, and Committee on Tidal Hydraulics (CTH) Report 3 (CTH 1965).

c. Types of material.

(1) The principal materials for jetty construction are stone, concrete, steel, and timber. Asphalt has occasionally been used as a binder. Various jetty structure types are presented in EM 1110-2-2904.

(2) Rubble-mound. The rubble-mound structure is a mound of stone of different sizes and shapes, either dumped at random or placed in courses. Side slopes and armor unit sizes are designed so that the structure will resist expected wave conditions. Methods of stability analysis for rubble-mound structures are presented in EM 1110-2-2904. Rubble-mound jetties are adaptable to any water depth and to most foundation conditions. Chief advantages are: structure settling readjusts component stones that increase stability, damage is repairable, and the rubble absorbs rather than reflects much of the wave energy.

(3) Sheet-pile. Steel, timber, or concrete sheet piles are often used for jetty construction in areas where wave conditions are not severe. Various formations of steel sheet-pile jetties include a single row of piling with or without pile buttresses; a single row of piling arranged to function as a buttressed wall; double walls of sheet piles held together with tie rods, with the space between the wall filled with stone or sand; and cellular-steel sheet-pile structures, which are modifications of the double-wall type. Cellular-steel sheet-pile jetties require little maintenance and are suitable for construction in depths to 12 m (40 ft) on all types of foundations. Corrosion is the principal disadvantage of steel in water.

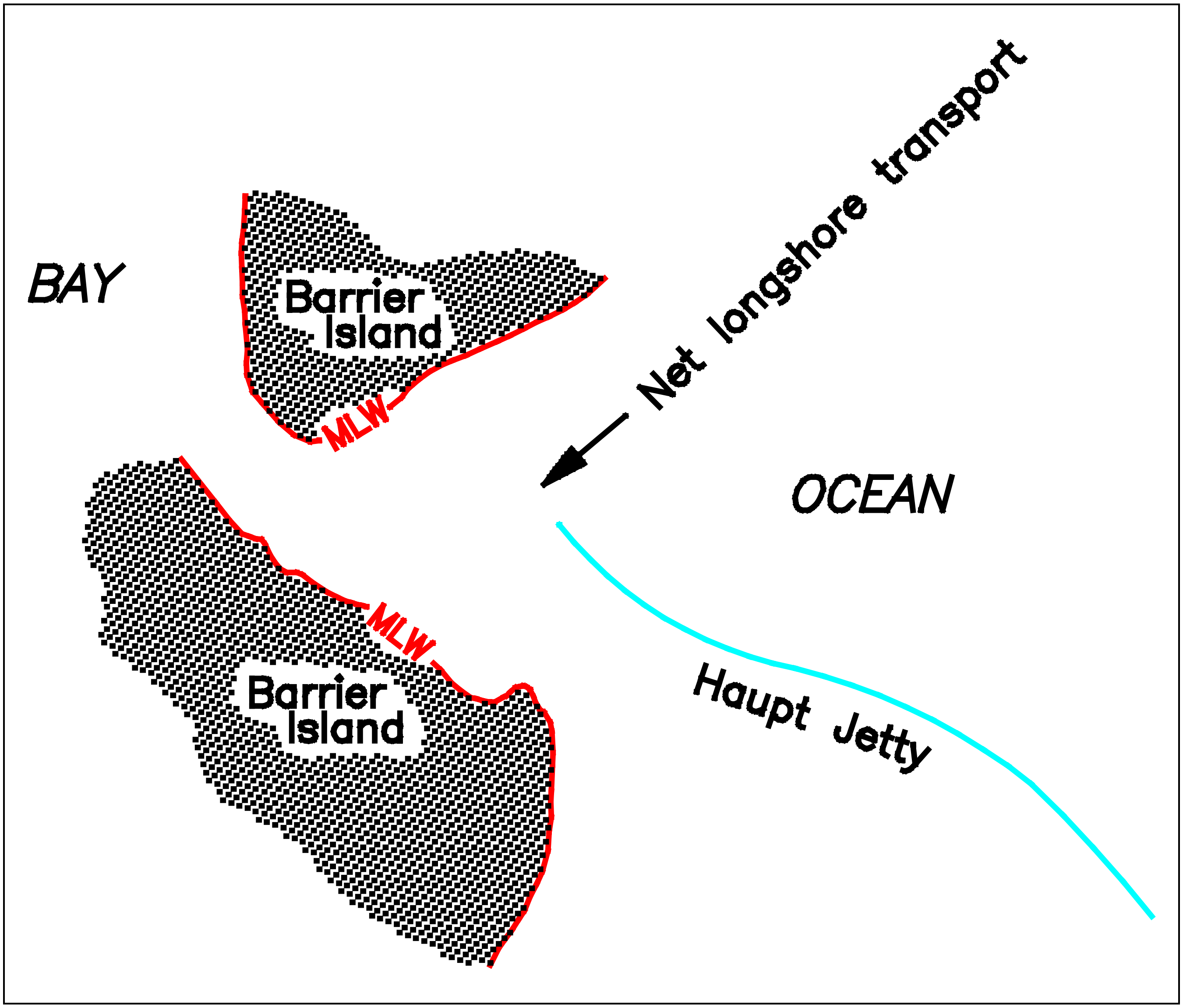

Figure 5-4. Schematic of a Haupt jetty system

d. Stability analyses.

(1) General. Jetty construction at inlet entrances will restrict the movement of tidal flows and nearshore sediment. Prediction of effects on structure stability and the nearby littoral environment, due to the changes in hydrodynamic processes, becomes an important step in the process of coastal structure design.

(2) Structure stability. Stability analysis of structure elements for rubble-mound jetties follows the Hudson formula outlined in EM 1110-2-2904. Design wave conditions of wave height, period, and direction should be selected based on long-term data, measured or hindcast. For sheet-pile jetties, appropriate wave forces under design wave conditions should be calculated according to procedures outlined in EM 1110-2-2904 and EM 1110-2-1614 to assure structure stability. Protection of structure toes, particularly at the channel side, is extremely important. Current scour at the toe area is a common cause of failure to jetty structures. The procedures of design and analysis of structure toe protection also are outlined in EM 1110-2-2904.

(3) Inlet stability. Overall stability of the inlet entrance channel should be analyzed using the methodology in Chapter 3 and for final design the modeling techniques presented in Chapters 6 and 7 may be

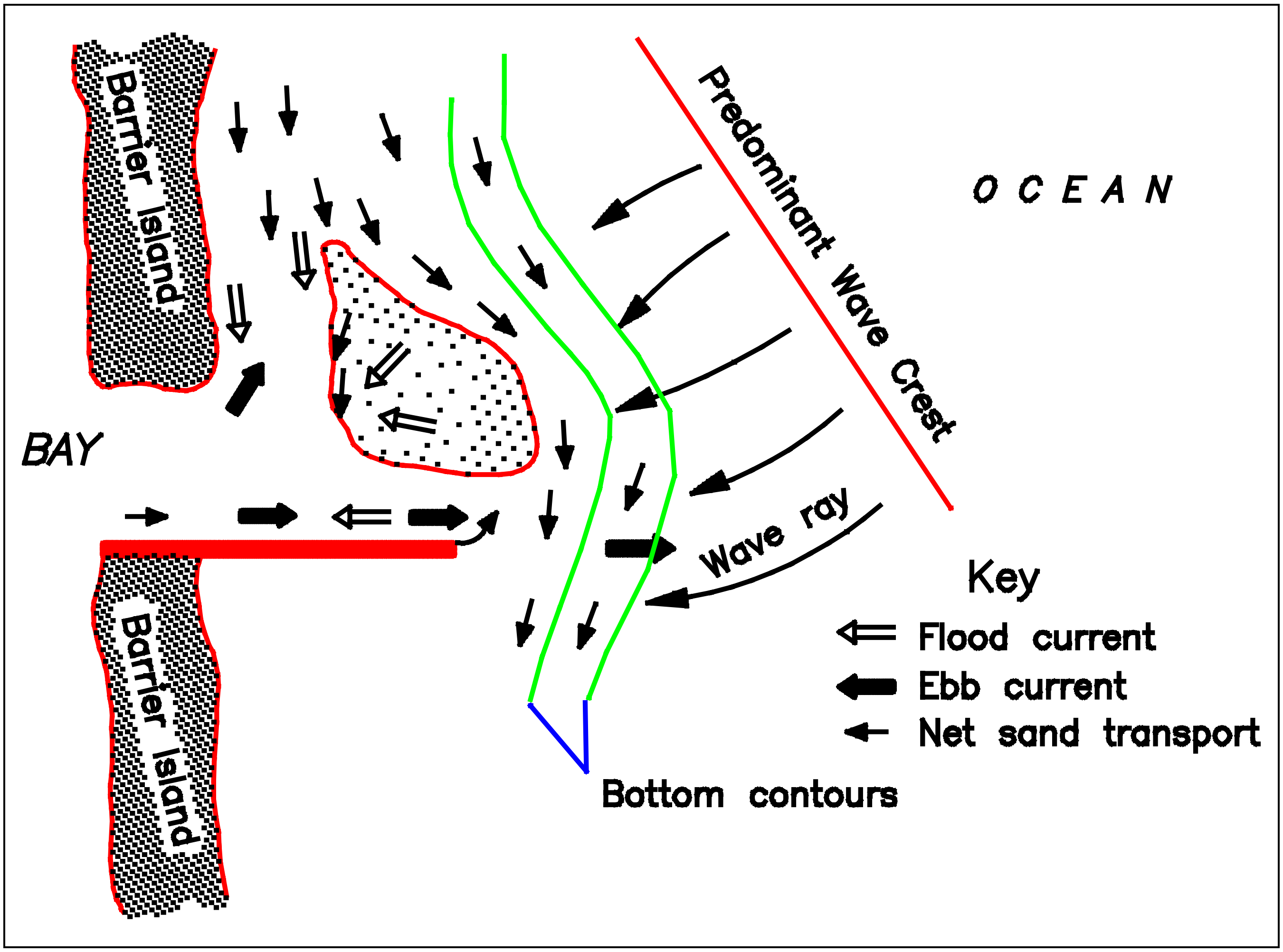

Figure 5-5. Schematic of a single downdrift jetty

required. The analysis should incorporate alterations designed for the inlet including jetty structures. If the entrance is unstable, bottom erosion may be expected and extreme caution is needed in the design of toe protection. If the entrance becomes unstable due to dredging, then excessive siltation may occur at the channel and, possibly, the bay area as well. Redesigning jetty alignment, increasing or decreasing the distance between twin jetties, or changing channel dimensions may be necessary for optimum tidal current patterns and magnitudes to improve inlet stability and to reduce maintenance requirements after the channel is improved.

(4) Shoreline changes. Effects on updrift and down-drift shorelines due to the presence of coastal structures should be thoroughly studied. Erosion control measures of sand bypassing should be considered if adverse impacts are expected. Chapters 6 and 7 discuss modeling techniques. EM 1110-2-1616 presents sand bypassing theory and technologies.

e. Other considerations.

(1) Jetty length. Jetty length should be determined by economic analysis of alternative plans. The maximum length will be the longer of either that producing a year-round design channel depth considering jetty and maintenance dredging cost on an annual basis, or that which extends the jetties beyond the breaker line of waves likely to be encountered by the design vessel. The two benefits will be evaluated on an average annual basis and will be compared with annual cost of the jetties required. Shorter jetties then should be considered at the expense of year-round navigation if the maximum length jetties result in an uneconomical project. Provisions for jetty extension at a later time should be included in a short jetty plan.

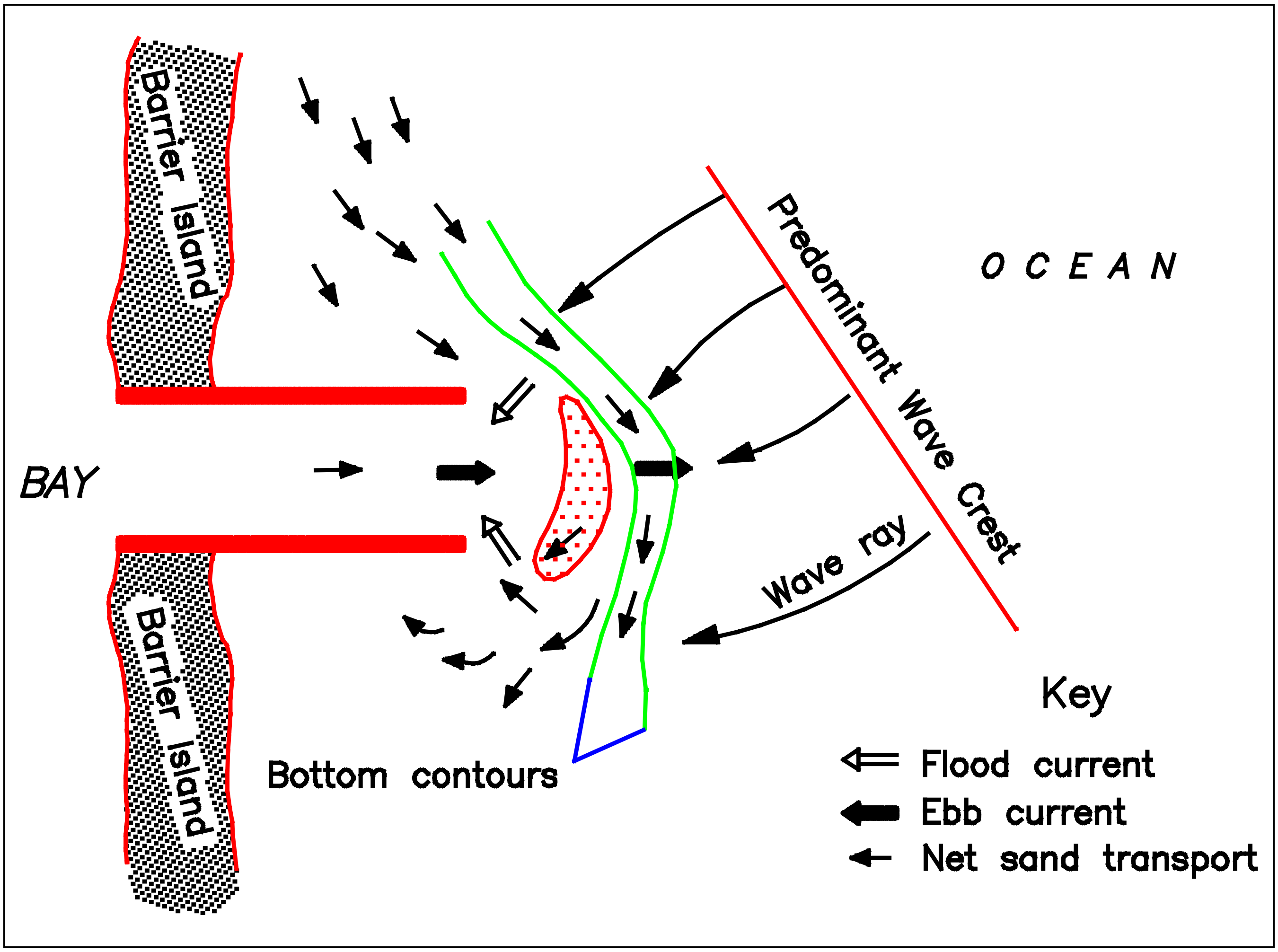

Figure 5-6. Schematic of a twin jetty system

(2) Permeability and overtopping. Rubble-mound jetties usually are not sand tight. The jetty function in littoral drift control can be reduced significantly due to structure permeability. Sand-tightening measures by constructing an impervious core layer, using geotextile fabric for leakage control, or asphalt to seal the pores, can be considered in the cost analysis. Leakage of littoral drift into the navigation channel also can occur through water overtopping low crested jetty structures. The design crest elevation should consider structure settlement and wave overtopping. A step-down type jetty may be designed when the offshore section is located in deeper water where littoral transport is at a minimum.

5-4. Sand Bypassing

The construction of jetties or breakwaters for navigation improvement at tidal inlets creates littoral barriers that interrupt the natural sand bypassing at the unimproved inlets. The resulting starvation of downdrift beaches may cause serious erosion unless measures are taken to bypass sand from the updrift side of inlets to downdrift beaches. Mechanical techniques may be used for sand bypassing, not only to minimize the shoreline erosion problem but also to reduce the potential of shoaling at the navigation channel. EM 1110-2-1616 discusses basic sand bypassing concepts and principles, presents advantages and disadvantages of various techniques and equipment, and provides guidance on developing technically feasible bypassing systems.

5-5. Economic Analysis

a. General. Optimum design of a coastal inlet improvement project requires studies of estimated costs and benefits of various plans and alternatives considering safety, efficiency, and environmental impacts. These studies are used to determine the most economical and functional channel alignment and design considering construction, maintenance, and replacement costs for various design levels. Economical optimization analysis should consider various elements involved in the development and maintenance of the project.

b. Channels. The economic optimization of a channel requires selection of several alignments and channel dimensions. Costs, which include initial construction, replacement, and annual maintenance, are developed for the various alignments and a series of dimensions are developed for each alignment. Benefits are developed from transportation savings with consideration of vessel trip time and tonnage, delays for tides, weather conditions, and effects of reduced depths in channels that have rapid shoaling tendencies. The optimum economic channel is selected from a comparison of annual benefits and annual costs for initial construction, maintenance, and replacement.

c. Structures.

(1) Optimization of structures such as jetties is accomplished by estimating the annual initial construction, replacement, and maintenance costs, and annual benefits for various design levels. Elements to be considered are: project economic life; construction cost for various design levels; maintenance and repair cost for various design levels; replacement cost for various design levels; benefits for various design levels; and probability of exceedance for various design levels.

(2) The project economic evaluation period for most coastal projects is 50 years. The design level or level of protection can be related to wave heights and water levels. The severity of these events may be represented by the probability of exceedance. Figure 5-7 shows the general relationship of exceedance probability versus the design level. Initial construction costs are estimated and annualized. Annual maintenance and repair costs can be estimated by multiplying the construction cost by the probability of exceedance of the design level. This cost estimate should compare with the actual cost of existing structures in similar coastal environments. Replacement cost should be annualized with the present worth of replacement cost considering appropriate interest rates and project life. Total cost as a function of design level is illustrated by Figure 5-8. A comparison of total costs and benefits as a function of design level is shown in Figure 5-9. Normally, the design level associated with the maximum net benefit will be selected for project design. If the net benefit point is not well-defined, it may be prudent to select a higher design level.

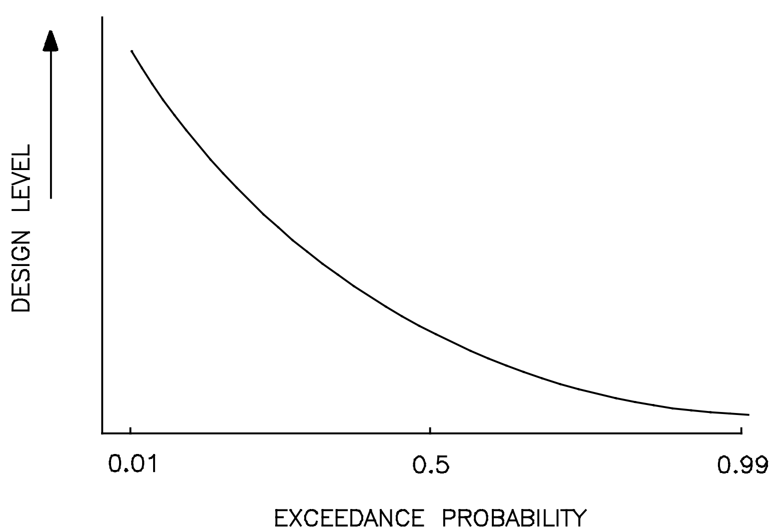

Figure 5-7. Exceedance probability versus design level

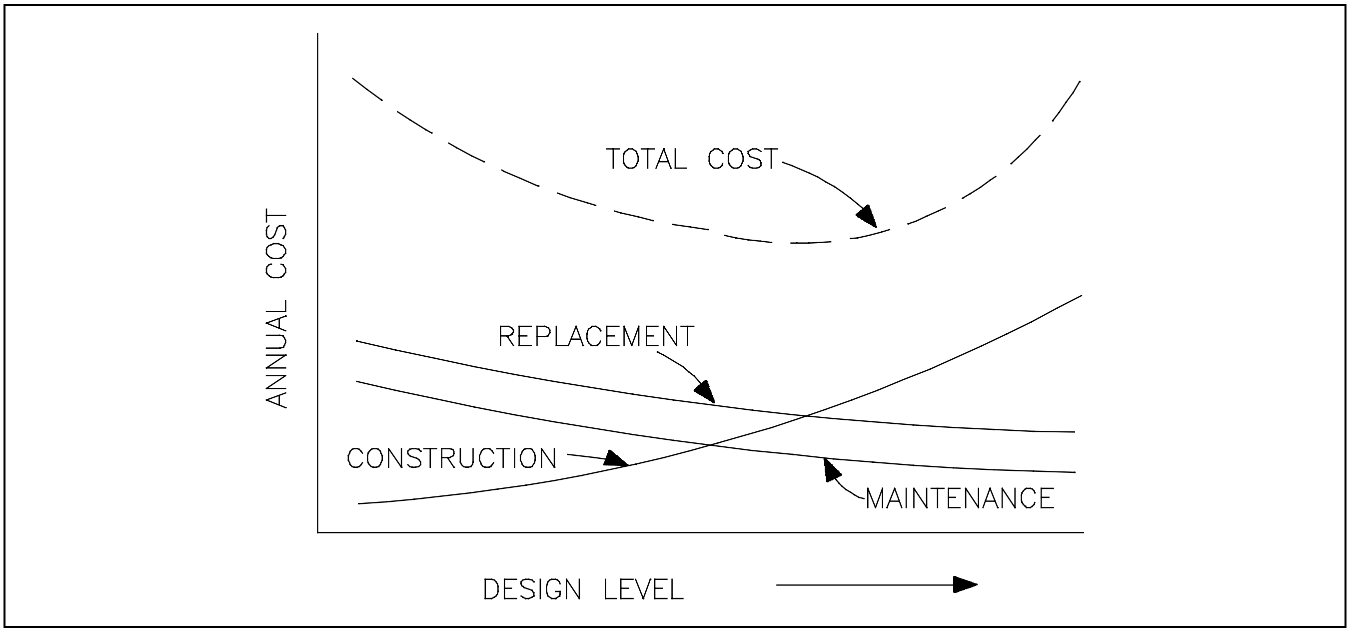

Figure 5-8. Project cost curves

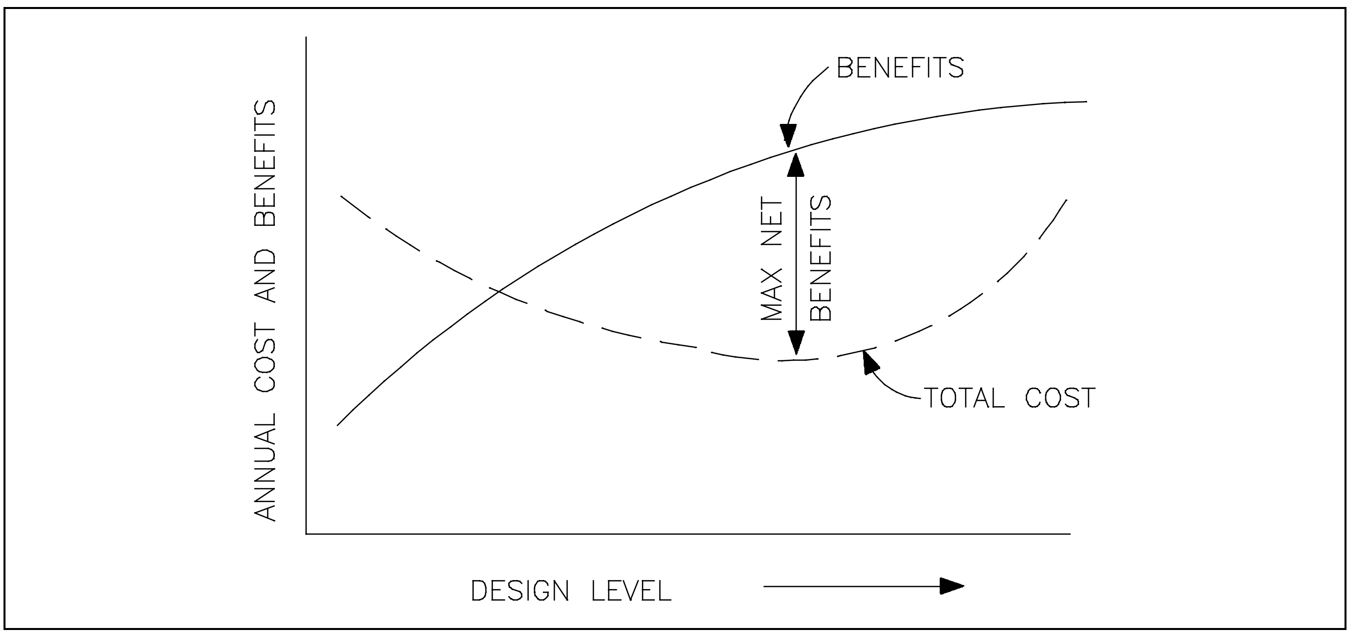

Figure 5-9. Benefits and cost versus design level